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# Anisotropic Anti-resonant Elements gives Broadband Single-mode Low-loss Hollow-core Fibers

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**Abstract:** Hollow-core fibers with node-free anisotropic anti-resonant elements give broadband low-loss fibers that are also single-mode. At 1.06  $\mu\text{m}$  silica-based fiber designs show higher-order-mode extinction-ratio  $>1000$  and losses below 10 dB/km over a broad wavelength range.

**OCIS codes:** (060.2280) Fiber design and fabrication; (060.5295) Photonic crystal fibers; (060.2310) Fiber optics

## 1. Introduction

Recently, hollow-core anti-resonant (HC-AR) fibers with a ‘‘negative-curvature’’ of the core-cladding boundary have been extensively studied owing to their low loss and wide transmission bandwidths [1–4]. The guiding mechanism of the HC-AR fiber relies on the combination of a inhibited coupling (IC) between the core and cladding modes and the anti-resonance [3]. The key unique feature of the HC-AR fiber is that the coupling between the core and cladding modes can be made anti-resonant (strongly inhibited) by suitably arranging the anti-resonant tubes in the cladding, which results in low loss and much broader spectral bandwidths. HC-AR fibers have been proposed with circular anti-resonant tubes [1,2]; ‘‘ice-cream cone’’-shaped anti-resonant tubes [5]; circular single nested and nested-in-nested anti-resonant tubes [2,3]; and adjacent nested anti-resonant tubes [4]. In contrast to the fibers reported in the literature, the present work consists of node-free anisotropic anti-resonant tubes placed on the inner wall of a capillary. By using anisotropic (e.g. elliptical) anti-resonant tubes instead of isotropic, i.e. circular ones, one gets at the same time (a) an increased negative curvature in the core, (b) a node-free (non-touching) design, and (c) a larger distance from the core to the outer capillary. All these properties could not be achieved simultaneously in the previous reported designs [1–5]. We find that HC-AR fibers with node-free elliptical nested elements offers two orders of magnitude lower leakage loss as well as effectively single-mode operation when compared to HC-AR fibers with circular nested elements.

## 2. Numerical results

First we optimized our proposed HC-AR fibers for six circular and elliptical anti-resonant tubes with a fixed  $R=15 \mu\text{m}$ ,  $t=0.42 \mu\text{m}$  at 1.06  $\mu\text{m}$ . Figure 1(a) shows the leakage loss as a function of air-hole radius for six circular tubes: it increases when the air-hole radius is enlarged. The lowest leakage loss was found  $\sim 0.05 \text{ dB/m}$  for an air-hole radius ( $r$ ) of 10.20  $\mu\text{m}$ , which is around one order of magnitude lower compared to when the air-holes are touching each other. This well-known result from using circular tubes is now compared to the case using elliptical anti-resonant tubes. We define ellipticity as  $\eta = r_y/r_x$ , where  $r_x$  and  $r_y$  are the radius of major and minor axis of the anti-resonant tubes respectively. Figure 1(b) shows that the lowest leakage loss of  $\sim 5 \text{ dB/km}$  was obtained for  $\eta \sim 0.65$ ,

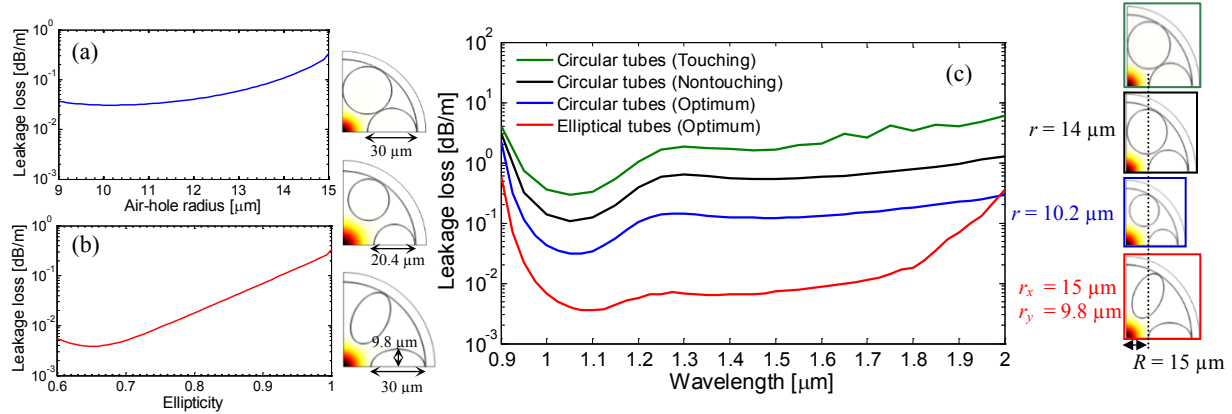


Fig. 1. Calculated leakage loss as a function of (a) air-hole radius, (b) ellipticity at 1.06  $\mu\text{m}$ , and (c) Comparison between the simulated leakage losses as a function of wavelength for different HC-ARFs. All considered structures have the same core radius  $R = 15 \mu\text{m}$  and uniform silica strut thickness  $t = 0.42 \mu\text{m}$ .

i.e.,  $r_x = 15 \mu\text{m}$  and  $r_y = 9.80 \mu\text{m}$ . It can be seen from Fig. 1(b) that the leakage loss can be reduced two orders of magnitude by suitably squeezing the anti-resonant tubes in the axis perpendicular to the radial direction.

The low-loss performance is also broadband, as figure 1(c) shows. The green curve shows the loss curve of six circular anti-resonant tubes in which tube walls are touching each other. The black curve shows the loss of HC-AR fiber having six circular anti-resonant tubes with the air-hole radius reduced to  $14 \mu\text{m}$  as to ensure the walls of adjacent tubes no longer touch; the leakage loss is slightly higher than  $0.1 \text{ dB/m}$  at  $1.06 \mu\text{m}$ . This is a well-known result from the circular case: separating the tubes there is a reduction of leakage loss [3]. However, the air-hole radius can be reduced even further as to minimize the loss, which is shown in the blue curve of Fig. 1(c): the leakage loss is lower in the entire wavelength regime ranging from  $0.90$  to  $1.8 \mu\text{m}$  than that shown in green and black curve. Finally, the red curve shows the loss spectrum of six elliptical tubes with the optimized air-hole radius; the leakage loss is 1-2 orders of magnitude lower than what is possible with circles and stays below  $10 \text{ dB/km}$  from  $1.0$ - $1.65 \mu\text{m}$ . We have also investigated the coupling between the core-guided modes and cladding modes, which is shown in Fig. 2. The first three cladding modes (red broken lines) have slightly larger  $\Delta n_{\text{eff}}$  than the first higher-order core-mode ( $\text{LP}_{11}$ ) which increases the possibility of strong phase-matching between the cladding modes and higher-order-modes (HOMs). This effect is more evident for the strong elliptical anti-resonant tubes ( $\eta \sim 0.60$ - $0.70$ ) in which coupling between the cladding modes and HOMs is more likely to occur. Figure 2(a) also shows the so-called HOM extinction-ratio (HOMER, i.e. loss-ratio between the HOMs and the  $\text{LP}_{01}$  mode). A maximal HOMER was found  $\sim 2500$  for  $\eta \sim 0.61$  whereas a fiber with circular anti-resonant tubes has  $\text{HOMER} < 10$ . The wavelength dependence of leakage loss and HOMER is shown in Fig. 2(b). The HOMER can be made in excess of 1000 and 150 for  $\eta \sim 0.61$  and  $\eta \sim 0.65$  in the spectral range  $1.0$ - $1.75 \mu\text{m}$  and  $0.95$ - $1.9 \mu\text{m}$  respectively, which indicates that the proposed HC-AR fiber can operate as an effectively single-mode fiber.

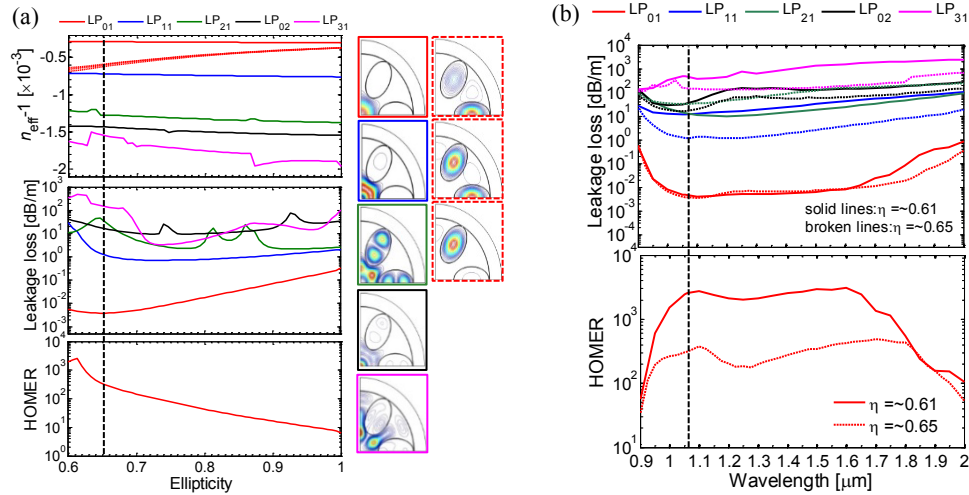


Fig. 2. (a) Effect of changing the ellipticity on relative effective index, leakage loss, and HOMER with a fixed  $R=15 \mu\text{m}$ ,  $r=0.42 \mu\text{m}$  and  $\lambda=1.06 \mu\text{m}$ . and (b) wavelength dependence of leakage loss and HOMER.

### 3. Conclusion

We proposed a hollow-core anti-resonant fiber design with node-free anisotropic nested elements, which allows low loss and effective-single mode guidance simultaneously over a broad wavelength range. This is because the anisotropy allows at the same time to get nested elements with increased negative curvature, a node-free design, and a large distance from the core to the capillary, all elements that improve the loss performance. We showed a silica-based design optimized for  $1.06 \mu\text{m}$  having a higher-order-mode extinction ratio over 1000 in the range  $\lambda = 1.0$ - $1.75 \mu\text{m}$  while keeping the  $\text{LP}_{01}$ -mode-loss below  $10 \text{ dB/km}$  in the  $1.0$ - $1.65 \mu\text{m}$  range. This design idea is generic and can be implemented in other HC-AR fiber types as well.

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